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# TECHNICAL NOTE

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SURVEY OF MATERIALS PROBLEMS RESULTING FROM LOW-  
PRESSURE AND RADIATION ENVIRONMENT IN SPACE

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# CONTENTS

	Page
SUMMARY . . . . .	1
INTRODUCTION . . . . .	1
PROBLEMS ASSOCIATED WITH LOW PRESSURES IN SPACE . . . . .	3
Environment Defined . . . . .	3
Possible Detrimental Effects - General Discussion . . . . .	3
Loss of bulk material . . . . .	3
Change in composition of bulk material . . . . .	3
Loss of very thin coatings . . . . .	4
Change in frictional properties . . . . .	4
Change in optical transmission . . . . .	5
Change in emissivity . . . . .	5
Material Classes . . . . .	5
Pure metals . . . . .	5
Alloys . . . . .	8
Ceramics and other inorganic compounds . . . . .	9
Plastics . . . . .	10
Lubricants . . . . .	10
PROBLEMS ASSOCIATED WITH RADIATION ENVIRONMENT IN SPACE . . . . .	11
Environment Defined . . . . .	11
Electromagnetic radiation . . . . .	11
Particulate radiations . . . . .	11
Possible Detrimental Effects . . . . .	12
Electromagnetic radiation . . . . .	12
Particulate radiations . . . . .	12
SUMMARIZING REMARKS . . . . .	13
Basic Research . . . . .	14
Laboratory Measurements for Purpose of Data Compilation . . . . .	14
Satellite Experiments . . . . .	15
REFERENCES . . . . .	15
TABLES	
I - MAXIMUM VAPORIZATION LOSSES COMPUTED FROM LANGMUIR EQUATION FOR VARIETY OF METALS AT 50 AND 75 PERCENT OF THEIR ABSO- LUTE MELTING POINT . . . . .	17
II - INFLUENCE OF AMBIENT PRESSURE ON RATE OF EVAPORATION OF TUNGSTEN IN 80 PERCENT ARGON, 14 PERCENT NITROGEN AT 2870° K . . . . .	18



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SUMMARY

On the basis of our present knowledge of the space environment, one might state that the exposure of materials to the radiation environment will present problems mainly with the impairment of the transparency of plastics and ionic solids due to ultraviolet radiation and with surface sputtering effects on emissivity and other thin film properties. The high vacuum in space will be of greater consequence in that it will render useless some members of practically all of the material classes. However, adequate solutions to most problems can be anticipated if enough information is at hand. This survey indicates that information is lacking at levels from the basic to the applied. A partial list of research areas in need of attack is included.

INTRODUCTION

The advent of the space age marked the beginning of a new demand on the materials engineer. He is now asked to supply materials that are capable of withstanding the rigors of a new environment, that of space. Two aspects of this new environment that are of concern to space-vehicle builders are the extremely low pressure and the radiation flux. Another aspect of the space environment that is of great concern is the presence of meteoroids and the possibilities of penetration and surface roughening of space vehicles. It is the purpose of this paper to discuss only the first two, namely, low pressure and radiation. The pressure in space is many orders of magnitude lower than that considered to be a good "high vacuum" in the laboratory until very recently. The radiation, while not different in kind from that encountered on the Earth's surface, is present in much higher intensities: The Earth's atmosphere is an effective shield for primary cosmic radiation and the short-wavelength end of the solar spectrum. The Van Allen radiation belts represent even higher concentrations of protons and other charged particles of high energy. The use of nuclear reactors as power sources in space vehicles will introduce

E-903

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radiation problems of much larger magnitude. However, the nature of these problems will not differ greatly from that of those associated with the use of nuclear reactors on the ground.

While the problem of using materials in high-vacuum and in radiation environments is not entirely new, it was generally confined to laboratory equipment, and requirements for long life and minimum weight were not critical. The space vehicle has need for such materials in a much wider variety of applications and imposes a reliability requirement of a type never before encountered.

The concern over the importance of ultra high vacuum and radiation to materials behavior has led to much discussion among specialists. An examination of the reports of conferences at which this subject was discussed discloses that, in general, confusion rather than clarification was the result. It is quite probable that the confusion was for the most part due to the fact that concepts taken as a matter of course in one discipline are entirely new to the worker in another field.

It is the purpose of this paper to discuss the possible effects of high vacuum and radiation on materials and to point out some of the needs for investigation in this area. Possible problems associated with flight through the upper atmosphere (below 150 miles (130 Int. naut. miles)) such as increased corrosion rates of refractory metals and surface heating due to atom recombination will not be considered. In particular, the points to be discussed are:

- (1) Present knowledge of the space environment
- (2) How high vacuum and radiation can affect the utility of materials
- (3) What properties will be affected in the various material classes
- (4) What effects can be predicted in magnitude from knowledge now at hand
- (5) What is needed in the way of research and the gathering of data to enable prediction of effects
- (6) What place a materials test satellite would play in the solution of the problems at hand.

This discussion was originally prepared for the guidance of the NASA Materials Satellite Test Committee in their considerations of proposals for materials experiments to be flown on space vehicles. It has been modified for presentation as a technical publication because it is believed that the subject under discussion is of general interest.

It is obvious that this discussion must of necessity be quite dependent on our present knowledge of the space environment. While the estimates of the general effects of space environment are thought to be fairly accurate, further experience with satellites and space probes may uncover entirely new problems and minimize some of those presently believed to be serious.

## PROBLEMS ASSOCIATED WITH LOW PRESSURES IN SPACE

### Environment Defined

The materials employed in space vehicles may be exposed to pressures lower than  $10^{-10}$  millimeter of mercury at a wide variety of temperatures. The temperature might be a steady-state temperature dictated by solar heating and heat loss to the very low space sink temperature; it may vary continuously as on the surface of a spinning vehicle; or it may be fixed by design (e.g., cryogenic fuel tanks or powerplant radiators). Vaporization rates increase exponentially with temperature, and maximum rates can be calculated if the equilibrium vapor pressure is known. The vaporization rate is independent of ambient pressure at low pressures, but begins to fall off when the mean free path decreases to the order of the dimensions of the evaporating surface. For example, experiments show that the vaporization from a platinum strip 0.12 centimeter wide begins to decrease from the computed maximum rate at pressures above 0.05 millimeter (refs. 1 and 2). The decrease in vaporization rate is the result of back-reflection to the surface of vaporizing atoms due to collisions with atoms or molecules in the gas phase. This phenomenon and the general subject of vapor pressure and vaporization-rate determination are discussed in detail in the section "Pure metals."

### Possible Detrimental Effects - General Discussion

Loss of bulk material. - Minimum metal thickness is an important goal in several areas. For example, the desire of minimal weight makes it desirable for fuel tanks, while heat-transfer considerations and weight make it desirable for radiators. Table I lists maximum losses in metal thickness at 50 and 70 percent of the absolute melting point for a variety of pure metals. It can be seen that an appropriate choice of material can be made for most purposes, but that it must be made on the basis of vaporization rate and not simply the melting point. A good example is the case of chromium and platinum. Although their melting points are only 48° F apart, the vaporization rates at 50 percent of their melting points vary by about a factor of  $10^{10}$ .

Change in composition of bulk material. - Exposure to vacuum of other than pure materials results in changes in composition. The

components of an alloy vaporize at different rates. The result may be a change in mechanical properties such as strength, hardness, and creep rate. Changes can also occur in physical properties such as electrical resistivity, thermal-expansion coefficient, and emissivity. Most plastics contain a plasticizer that has an appreciable volatility. Its loss results in cracking and crazing due to shrinkage and in an increase in brittleness. Discoloration may also result. Many inorganic compounds decompose rather than melt. Consequently, exposure of ceramics to high vacuum at high temperatures may result in interdiffusion of the components or chemical reactions in addition to simple composition changes: Alteration in both mechanical and physical properties can be anticipated.

Loss of very thin coatings. - Thin coatings have a variety of uses in space vehicles. For example, metals and paints are used for internal temperature control. Metal films also have a use in printed circuits for electronics and strain gages. Loss of material from a thin film can result in several types of undesirable effects. Loss of bulk can rapidly render a film useless if the electrical resistivity is critical. Vaporization can also result in loss of adherence. It should be pointed out that solar heating may yield much higher film temperatures and thus higher loss rate if the substrate has a low thermal conductivity.

Change in frictional properties. - Lubrication of sliding parts is accomplished by two mechanisms. For low loads, a thin film of a suitable solid or liquid separates the sliding surfaces and reduces the coefficient of friction. For higher loads, the separation of the sliding surfaces is by a chemical compound of the metal surface and the lubricant; in some cases, the adsorbed gas or oxide layer on the metal surface is essential to the formation of the compound. This compound film is continually torn off and re-formed. It reduces friction because its strength is lower than the metal-metal weld that would be formed in its absence. Exposure to high vacuum may result in the loss of both types of lubricant.

While it may be possible to seal and pressurize some of the sliding systems and thus retain a liquid lubricant, the lower reliability of such a system and the fact that sealing is almost impossible in some cases (e.g., gimbal mounts, antenna or solar collector orientation mechanisms) have focused attention entirely on solid lubricants. Damage to these could occur because the lubricant is lost by evaporation or decomposition or because oxide layers or adsorbed films that are necessary to their effectiveness would be lost and could not re-form under vacuum conditions.

The loss due to wear or decomposition of preformed lubricant films such as iron sulfide would be serious. Finally, the loss of oxide films or adsorbed gases might cause welding of sliding surfaces whose operation normally does not require lubrication.



Change in optical transmission. - Changes in optical transmission can result from the crazing of plastics that accompanies the loss of plasticizer. It is also possible that glasses may devitrify at high temperatures as the result of composition changes.

Change in emissivity. - Evaporation normally results in a roughening of the surface. Consequently, changes may be anticipated in emissivity and reflectivity. Surface roughening is the consequence of the variation in free energy for the various crystal planes. Material will be lost at the greatest rate from planes of highest energy, and the surface planarity will change as the surface of each grain tends to adopt the configuration having the lowest energy.

Changes in emissivity and reflectivity can also be anticipated for metals that under normal atmospheric conditions are covered with a protective oxide film (e.g., aluminum and chromium).

#### Material Classes

Pure metals. - Loss of bulk material: The rate of vaporization varies rapidly with temperature, since it is a function of the vapor pressure, which itself varies as the exponential of  $1/T$  (ref. 3). The Langmuir equation for rate of vaporization  $\mathcal{A}$ , in grams/(cm<sup>2</sup>)(sec) is

$$\mathcal{A} = \frac{P}{17.4} \sqrt{\frac{M}{T}} \quad (1)$$

where  $P$  is vapor pressure (mm Hg),  $M$  is molecular weight, and  $T$  is temperature (°K). The temperature variation of the vapor pressure  $P$  can be written as

$$P = \text{const. } e^{-L/RT} \quad (2)$$

where  $L$  is heat of vaporization and  $R$  is the gas constant. The Langmuir equation (1) is based on the assumption that all the atoms that escape from the surface are lost permanently. It thus yields the maximum rate of loss. Table I lists vaporization losses thus computed in terms of inches of thickness per year at two temperatures for a variety of metals. At sufficiently high ambient pressures, all escaping atoms are not lost permanently because some of them are reflected back to the surface by collisions with atoms or molecules in the gas phase. The common use of cover gas to reduce loss of material by vaporization during melting is based on this phenomenon. The net loss of material is thus lower than the maximum computed from equation (1). The lowest pressure at which measurable deviation occurs is approximately that for which the mean free path is of the order of the dimensions of the evaporating surface.

The following table indicates the order of variation of mean free path with pressure for silver:

Pressure, mm Hg	Mean free path, cm
760	$2 \times 10^{-5}$
1	$1.5 \times 10^{-2}$
$10^{-3}$	15
$10^{-6}$	$1.5 \times 10^4$
$10^{-12}$	$1.5 \times 10^{10}$

Experimental data on evaporation rates for tungsten over an appreciable pressure range are listed in table II.

Vapor-pressure determinations at ambient pressures of  $10^{-5}$  to  $10^{-6}$  millimeter, where the evaporating material strikes cold walls and sticks, do not suffer in accuracy from the back-reflection phenomenon. It is not known whether back reflection might appreciably reduce evaporation rates from vehicle surfaces in space where second and later collisions can re-direct material back to the surface. The problem is being studied theoretically at the NASA Lewis Research Center.

Experimentally determined vapor pressures are available in the literature for practically all pure metals (refs. 3 and 4). These were determined under conditions for which the back-reflection phenomenon was not a source of error. The maximum rate of vaporization in space vacuum can thus be computed directly.

The Knudsen method is that commonly used for vapor-pressure determination. It is used for all materials for which a container capsule can be made. This method employs a capsule containing the vapor in equilibrium with the solid (or liquid). Vapor is lost through a pinhole at a rate low enough to prevent disturbance of the equilibrium. The loss in weight of the capsule or the gain in weight of a target plate is measured. The rate of loss of material through the pinhole or orifice of known size provides a basis for calculation of pressure (thus the vapor pressure of the sample) inside the capsule.

The Langmuir method is used for vapor-pressure determination when no container material is available for construction of a Knudsen cell; tungsten, molybdenum, and other refractory metals fall into this category. The rate of vaporization is measured directly, and the vapor pressure is computed by means of the Langmuir equation (1).

E-903

One area in this field that requires research pertains to the possible reduction of vaporization rate by an oxide layer on the surface. Loss of metal from a surface covered with a dense oxide would be controlled by the rate of diffusion of metal atoms through the oxide layer rather than by the vapor pressure of the metal. This situation would hold true especially at low temperatures, because the diffusion rates would be low and the metal oxides formed at low temperatures are less porous than those formed at high temperature. At high temperatures, where the vapor pressure is high enough to make measurements convenient, metals generally form oxides that are porous and thus do not interfere with the measurement. Aluminum appears to be the exception. The vapor-pressure data for aluminum are generally suspected to be low because the dense oxide forms very rapidly even at low temperatures and very low oxygen pressure. It will be noted from table I that the rates of vaporization of aluminum and magnesium at 50 percent of their melting points differ by a factor of  $10^{20}$ . The variations in cohesive forces for these quite similar atoms are much too small to account for this large difference. Also, the oxide of magnesium is known to be porous, while that of aluminum is nonporous.

The aspects of this problem that are attractive with respect to space application are that oxide coatings may reduce evaporation rates sufficiently in some cases to permit the use of metals that would evaporate much too rapidly in the clean state. It must be pointed out that, even though the oxide would probably be lost slowly as the result of erosion by collision with atomic and meteoroidal particles, the protection afforded by it would not decrease rapidly, because the reduction in vaporization rate is in proportion to the fraction of the surface covered. This is a distinctly different case from the oxidation protection of some refractory metals by coatings in which the presence of even one pinhole can yield catastrophic results.

Loss of very thin coatings: While evaporation losses from thin films of the pure metals can be computed as outlined previously, due regard must be taken of the possible temperature gradient mentioned in the section on "Loss of very thin coatings." If the metal film is deposited on a ceramic or plastic substrate that has a low thermal conductivity, solar heating may result in a higher film temperature than that measured in the substrate. Metal films deposited by vacuum evaporation to small film thicknesses are generally far from uniform in microstructure. The metal atoms condense as they strike the surface, and the resulting film contains highly disordered regions. It is to be expected that the vaporization loss from a thin film will not be uniform, the rate being higher from the disordered regions. It is possible that from these disordered regions the rate may be even higher than that calculated from the Langmuir equation. The magnitude of this effect is difficult to predict; and, since the coherence of films is important for electrical applications, an

investigation of this effect would be worthy of some effort. The investigation might be made from two points of view. One would be to study the problem in a general way, while the other would be to observe the behavior of a system that is needed for a specific device.

Change in frictional properties: Very little information is available on the frictional behavior of metals at very low pressures. The data at hand on outgassed specimens of a few pure metals indicate that the friction coefficient shows a tenfold increase as the pressure is reduced from atmospheric to about  $10^{-6}$  millimeter (ref. 5). These data are from friction measurements during single-pass experiments. No long-time effects such as abrasion were studied. Data on four plastics that had been freed of contaminant films by gentle heating and evacuation at pressures below  $10^{-5}$  millimeter indicate that the adhesion theory of friction can be applied to plastics in vacuum (ref. 6).

Research is needed in the entire low-pressure region in order to gain an understanding of all the problems as well as to arrive at possible general solutions. Since the state of knowledge is so fragmentary in this field, it would seem necessary to attack the problem at the same time from the developmental point of view. Meaningful data in this field require accurate knowledge and careful control of the state of the surface and environmental conditions. Thus, much work remains to be done in ground laboratories, and satellite experiments should only be in the nature of proof tests.

Change in emissivity: Emissivity changes can result in pure metals, as outlined previously, because of the loss of oxide films or the roughening due to selective evaporation from some crystal planes. Emissivity and absorptivity studies can be performed in the laboratory. Their utility in predicting the behavior of materials in a spacecraft depends on the success with which the experiment duplicates both the condition of the surface and the radiation conditions. It is expected that much work will be required on the ground as the environmental conditions in space are better defined. Final proof tests will probably be required in a satellite, especially in order that the meteorite damage effects may also be incorporated. Strong recommendations for satellite experiments in this area have been made by the Materials Advisory Board of the National Academy of Sciences (ref. 7). They conclude that space-vehicle experience and experiments are required because of the great difficulty of simulating some of the environmental parameters (e.g., macro- and micro-meteorites, solar wind protons, Van Allen radiation) and the even greater difficulty of simulating several of them simultaneously.

Alloys. - Loss of bulk material: The rate of vaporization of an alloy cannot be predicted solely on the basis of the vapor pressures of its component elements; in general, the measured rate is much lower. In

addition, one needs to know the partial pressures of the component elements in the vapor in equilibrium with the alloy and also the diffusion coefficients of the component elements in the solid alloy. Except for a few isolated cases, the study of the vaporization of alloys is of quite recent origin, and very little of the required information is in existence. Research in this field is sorely needed. It is of such nature that it must be done on the ground. Vacuums in the range  $10^{-5}$  to  $10^{-6}$  millimeter are adequate for most of this work.

Change in composition: Alloys will change in composition as the result of evaporation. As a result, their mechanical and physical properties will also change. It should be noted that such changes will not, in general, be predictable from data obtained by preparing alloys of various compositions by the common techniques. This difference in behavior arises from the fact that gradients in composition in the vaporizing alloy will exist because the components will reach the surface at different rates by diffusion from the interior and will be lost from the bulk at different rates. Alterations in bulk composition can occur for some materials and affect mechanical behavior if the components generally present are dependent on air atmosphere. The oxide strengthening of nickel and nickel alloys (resulting from testing in air) has been studied at NASA Lewis (ref. 8) and at the Naval Research Laboratory (ref. 9). Additional data on changes in mechanical and physical properties accompanying vaporization losses are needed and should be obtained for other alloys whose rates of vaporization are satisfactorily low. This work would not require a satellite.

Loss in very thin coatings, change in frictional properties, and change in emissivity: The comments on these subjects in the section "Pure metals" are also pertinent here.

Ceramics and other inorganic compounds. - Loss of bulk material: The decomposition temperatures of inorganic compounds are generally lower than the temperatures at which measurable loss occurs by vaporization of the inorganic molecule as a whole. Very little data exist that would be useful in predicting rates of loss by either decomposition or vaporization of these materials. Research is needed to measure decomposition pressures and rates, to identify the vapor-phase species, and to determine the chemical mechanisms involved.

Changes in composition: Changes due to decomposition may change the nature of the material in such a way as to render it useless for the particular application. On the other hand, changes in composition might be also insignificant. An example of the first type would be the conversion to a low-melting compound. An example of the second type might be the conversion of a lower oxide to a higher one of acceptable properties. The extension of these concepts to thin coatings, frictional properties,

and emissivity is obvious. Research is needed in this field and would be more amenable to ground research than to a satellite experiment.

Plastics. - Composition changes: Plastics can be thought of generally as composed of very large molecules that are formed as the result of the cross-bonding of smaller but still large molecules. Also present in a large number of varieties is a plasticizer; typical plasticizers are dimethyl, diethyl, and dibutyl phthalate. The plasticizer is more readily lost by vaporization than the polymer itself. Loss of plasticizer over long periods of time at room temperature gives rise to the familiar crazing of plastics such as methyl methacrylate. When higher temperatures are encountered, the polymeric material also decomposes. The very large polymer molecule breaks apart at its weaker bonds, and smaller fragments (of higher vapor pressure) are formed. Exposure to vacuum at the higher temperature accelerates their loss. The loss of plasticizer alone generally results in an increase in brittleness, while the decomposition of the polymer causes changes in other properties as well.

The behavior of plastics in high vacuum and at elevated temperatures is the subject of intensive study at present. Both bulk materials and coatings are under study at a number of laboratories under Air Force WADC Materials Laboratory sponsorship (ref. 10). It is believed that this work will soon result in the formulation of satisfactory materials for a variety of applications. The studies under way are concerned with the effects of both heat and solar radiation, since the damage due to both is very much the same in nature and the two types of experiment can be easily combined. Optical properties are also being studied in some of the programs, but a great deal of work is needed in this area.

Changes in friction properties: Very little is known about the effect of vacuum on friction properties of plastics. Research is needed in this field.

Lubricants. - As mentioned in the general discussion of changes in frictional properties, the lubricants of interest for surfaces exposed to space vacuum are solids. Solid lubricants in terrestrial use are of two types, either preformed (e.g., iron sulfide) or formed and re-formed during operation. The latter type, whose success depends on the continuous presence of reactants that are usually gases or liquids of high volatility, is of no use in this application. The solid lubricants of interest are those that can be preformed on the surface and that can withstand the requisite number of cycles of operation. Operation in space vacuum can cause them to vaporize or decompose. Research is needed to define the conditions under which the various solid lubricants are effective and to determine which of them will be useful under space conditions. While laboratory tests under carefully controlled conditions are of first concern, actual tests in satellites may also be necessary for final proof testing.

## PROBLEMS ASSOCIATED WITH RADIATION ENVIRONMENT IN SPACE

## Environment Defined

Electromagnetic radiation. - The major fraction (93 percent) of radiant energy from the Sun arrives as light of wavelengths between 0.3 and 2 microns. (The wavelength range for visible light is 0.4 to 0.7 microns.) About 1 percent of the energy is of wavelengths less than 0.3, and 6 percent is of wavelengths longer than 2 microns.

Particulate radiations. - Cosmic rays: Vehicles in space will be exposed to primary cosmic radiation, which consists mainly of protons but also includes particles of higher mass. The total flux is of the order of  $10^5$  particles per square centimeter over a 24-hour period, and the particle energies range from about 100 to  $10^7$  Mev (ref. 11). The ionization rate at these flux levels is about 24 milliroentgens per 24 hours. No detrimental effects are anticipated from cosmic rays in materials of any type (including semiconductors). It might be pointed out, however, that the ionization rate at this flux level is near the maximum permissible rate for human beings.

Van Allen radiation: The Van Allen radiation belts contain electrons of energy greater than 13 Mev and protons whose energy ranges to 700 Mev. The flux estimates by Van Allen on the basis of early experiments are in the range of 10 to 100 roentgens per hour, and more recent data from Explorer VI indicate that the peak level may be as high as 1000 roentgens per hour in the vicinity of the geomagnetic equator and also elsewhere during increased solar activity. By way of comparison, the fluxes in nuclear reactors are of the order of  $10^5$  to  $10^6$  greater than these.

Particles of lower energy: There are present in the space environment other particles that have low energy compared with cosmic rays and Van Allen radiation but whose interception by a space vehicle would result in energy transfer that would yield similar results. These particles are the protons and helium ions composing the solar wind and the neutral gas atoms (H beyond 600 miles (520 Int. naut. miles), and H, N, and O at lesser distances). The solar wind particles originate in the Sun's corona and vary drastically in number and energy with solar conditions. Their average number is  $10^3$  per cubic centimeter, and their average energy is 50 electron volts. Their number is estimated to rise to  $10^5$  per cubic centimeter under some conditions, and their energy can be as great as  $10^4$  electron volts. The concentration of neutral atoms is of the order of  $10^5$  atoms per cubic centimeter at 300 miles (260 Int. naut. miles) and falls off rapidly with altitude. A good deal of detailed information is needed on the solar wind.

E-903

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### Possible Detrimental Effects

Electromagnetic radiation. - Materials are commonly exposed in the terrestrial environment to all but the extended short-wavelength end of this spectrum. In metals, the ultraviolet of short wavelengths can produce photoelectric emission. However, the flux is too low to cause serious effects, either in the surface layers or in the bulk. An estimate has been made that in one year, two atoms in every 10,000 in a 1-centimeter cube of copper will produce photoelectrons if every photon intercepted is active in this production.

The damage to plastics and elastomers caused by ultraviolet radiation results from ionization and excitation of electrons. The changes are irreversible and include free-radical formation, polymerization, degradation (cleavage of carbon chains), and gas formation (oxygen, hydrogen, and low-molecular-weight hydrocarbon gases). These phenomena also occur with gamma-ray dosage and are thus also of concern in the application of plastics in other areas. A large effort is being expended on the development of radiation-resistant plastics and elastomers.

Some inorganic solids are also susceptible to damage by ultraviolet radiation. The discoloration of the alkali halides, quartz, glass, and MgO are examples. The mechanism involved is ionization and the production of free electrons that migrate to vacant negative-ion sites in the lattice to form F-centers. In addition to causing loss in transparency, the F-center formation results in increased brittleness and hardness as well as a slight increase in strength. Little quantitative information useful to instrument designers is available on the extent of coloration with dose and temperature, but there are indications that appreciable darkening can occur under some conditions. Window materials should be examined from this point of view before they are incorporated into equipment. The experimental techniques involved are quite simple.

Particulate radiations. - Cosmic rays: As mentioned previously, the flux level for cosmic radiation is too low to be a cause for concern with regard to materials damage.

Van Allen radiation: The information concerning the composition of the Van Allen belts is still fragmentary, and future data may require alteration of views. However, damage to materials of all types by nuclear radiation has been the subject of intensive research for many years, and the damage by the particles known to be present in the Van Allen radiation is fairly well understood. The impossibility of accurate prediction of the magnitude of the effects is due almost entirely to the present uncertainties as to the composition of the Van Allen radiation. The present indications are that the radiation levels are too low to cause concern over damage to any material unless the satellite orbit causes it to remain in the Van Allen regions for very long periods of



time. It has been estimated (ref. 11) that damage to a transistor would become excessive after an orbital time of 8 months in the radiation belts. The higher sensitivity of biological systems would make a greater demand that manned vehicles avoid this.

Particles of lower energy: The solar-wind ions and the neutral atoms can cause sputtering. Sputtering is the ejection of atoms from the surface as the result of the transfer of energy to them from an atom or molecule that strikes the surface - in effect, a billiard-ball type of process. The theoretical and experimental information in this field is limited and inconclusive and does not permit accurate estimates. There is little doubt, however, that devices and instrumentation employing thin films will be affected on long exposure.

Only recently, mainly with the work of Wehner (ref. 12), has the mechanism by which sputtering occurs begun to be understood. From a fundamental viewpoint, much remains to be done in the field at energies in the range from 50 to 100 electron volts and even more so in the high-voltage range. The subject requires very careful experimentation and would not benefit at all from satellite experiments.

#### SUMMARIZING REMARKS

On the basis of present knowledge of the space environment, one might state that the exposure of materials to the radiation environment in space will result in problems mainly with the impairment of the transparency of plastics and ionic solids due to ultraviolet radiation and with surface sputtering effects on emissivity and other thin-film properties. The high vacuum in space will be of greater consequence in that it will render useless some members of practically all the material classes. However, adequate solutions to most problems can be anticipated if enough information is at hand.

This survey, which is by no means exhaustive, indicates that investigations at all levels are needed to provide information on the effect of the low-pressure and radiation environment in space on the behavior of materials. Since some of the information needed will require extensive study, it is obvious that research in these areas should receive immediate attention in order to minimize "crash efforts" in the future. The following is a partial list of research areas classified according to the mode of attack. The large majority of these studies can be performed in ground laboratories with good vacuum systems in the  $10^{-6}$ -millimeter range. The need for ultra-high-vacuum facilities ( $10^{-8}$  mm or better) is indicated where it exists.

### Basic Research

Basic research is needed in the following areas:

- (1) The influence of oxide layers on vaporization rates. Ultra-high-vacuum conditions will be needed here - not for the measurement of rate, but in order that very clean surfaces can be maintained when desired.
- (2) The vaporization of alloys
- (3) Vaporization of thin films containing disordered regions and other strains
- (4) Lubrication - stability of solid-film lubricants, frictional behavior at pressures below  $10^{-3}$  millimeter. Ultra-high-vacuum conditions are needed here to provide very clean surfaces.
- (5) Vaporization and decomposition of ceramics and other inorganic compounds: Measurement of decomposition pressures, identification of vapor-phase species, determination of the chemical mechanisms involved in the decomposition reactions.
- (6) Sputtering of surface layers by ions and neutral atoms and molecules: Mechanism and extent of sputtering for particle energies over entire range up to 1 Mev.

### Laboratory Measurements for Purpose of Data Compilation

Laboratory research should be conducted on the following:

- (1) Vaporization rates of pure metals - those instances for which oxide films may introduce error and prevent extrapolation to space vacuum. Ultra-high-vacuum conditions are needed for surface cleanliness.
- (2) Vaporization rates and partial pressures of alloys
- (3) Physical and mechanical properties of alloys subjected to vacuum environment
- (4) Electrical resistivity and optical properties of thin films undergoing evaporation
- (5) Solid lubricants - determination of the range of conditions over which specific lubricants are effective

- (6) Emissivity of coatings - determination of changes caused by the separate aspects of the space environment; for example, vacuum, sputtering, and ultraviolet radiation
- (7) Electrical, physical, and mechanical properties of ceramics and other inorganic compounds after exposure to conditions causing vaporization and decomposition
- (8) Plastics - effect of vaporization on optical and frictional properties
- (9) Ultraviolet discoloration of plastics, ionic solids, and glasses

### Satellite Experiments

The instances are rare indeed in which the behavior of a device of any complexity could be completely predicted from a knowledge of the behavior of its component parts. Obviously, a final proof test in a satellite will be desirable if at all possible before any device is used in a critical application such as an interplanetary vehicle. In addition, there are some materials experiments for which the space environment cannot be adequately simulated on the ground. One example is the meteoroid penetration study. Another is the determination of the combined effects on emissivity of causes such as evaporation, sputtering, meteorite damage, ultraviolet radiation, and so forth.

Lewis Research Center  
National Aeronautics and Space Administration  
Cleveland, Ohio, July 20, 1960

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TABLE I. - MAXIMUM VAPORIZATION LOSSES COMPUTED FROM LANGMUIR  
EQUATION FOR VARIETY OF METALS AT 50 AND 75 PERCENT  
OF THEIR ABSOLUTE MELTING POINT<sup>1</sup>

Metal	Melting point, °F	50 Percent of absolute melting point		70 Percent of absolute melting point	
		Temper- ature, °F	Loss, in./yr	Temper- ature, °F	Loss, in./yr
C	6700	3120	$7.5 \times 10^{-5}$	4550	21.7
W	6170	2855	$2.9 \times 10^{-9}$	4180	$4.2 \times 10^{-3}$
Ta	5425	2480	$3.6 \times 10^{-11}$	3660	$3.3 \times 10^{-4}$
Mo	4760	2150	$1.4 \times 10^{-8}$	3195	$1.1 \times 10^{-2}$
Nb	4380	1960	$4.6 \times 10^{-15}$	2930	$1.5 \times 10^{-6}$
Cr	3272	1405	$2.0 \times 10^{-3}$	2150	115
Pt	3224	1380	$8.4 \times 10^{-14}$	2120	$3.5 \times 10^{-6}$
Fe	2800	1170	$7.7 \times 10^{-9}$	1820	$1.4 \times 10^{-2}$
Co	2723	1130	$8.1 \times 10^{-12}$	1770	$8.7 \times 10^{-5}$
Ni	2650	1095	$2.1 \times 10^{-11}$	1720	$2.9 \times 10^{-4}$
Be	2340	940	$1.6 \times 10^{-9}$	1500	$6.6 \times 10^{-3}$
Al	1220	380	$4.8 \times 10^{-23}$	715	$2.6 \times 10^{-12}$
Mg	1200	370	$1.0 \times 10^{-3}$	700	53

<sup>1</sup>Calculations based on vapor-pressure data from refs. 3 and 4.

TABLE II. - INFLUENCE OF AMBIENT PRESSURE ON RATE OF EVAPORATION OF  
TUNGSTEN IN 80 PERCENT ARGON, 14 PERCENT NITROGEN AT 2870° K<sup>1</sup>

[Diam. of filament, 0.00978 cm.]

Ambient pressure, cm	Rate of evaporation, g/(cm <sup>2</sup> )(sec)×10 <sup>9</sup>
0	230
1	57.5
5	23.5
10	20.5
25	10.3
50	5.4
70	4.2
165	2.0

<sup>1</sup>From ref. 3, p. 80.

<p>NASA TN D-477 National Aeronautics and Space Administration. SURVEY OF MATERIALS PROBLEMS RESULTING FROM LOW-PRESSURE AND RADIATION ENVIRONMENT IN SPACE. Robert A. Lad. November 1960. 18p. OTS price, \$0.50. (NASA TECHNICAL NOTE D-477)</p> <p>The possible detrimental effects of the low-pressure and radiation environments on the utility of pure metals, alloys, ceramics and other inorganic compounds, plastics, and lubricants are outlined. The state of knowledge with regard to the possibility of predicting behavior is discussed for each of the material classes. The specific areas are described in which further research and gathering of engineering data are needed. The role of space experiments in the various areas is indicated.</p>	<p>I. Lad, Robert A. II. NASA TN D-477</p> <p>(Initial NASA distribution: 25, Materials, engineering; 26, Materials, other; 32, Physics, solid state; 47, Satellites; 48, Space vehicles; 52, Structures.)</p>	<p>NASA TN D-477 National Aeronautics and Space Administration. SURVEY OF MATERIALS PROBLEMS RESULTING FROM LOW-PRESSURE AND RADIATION ENVIRONMENT IN SPACE. Robert A. Lad. November 1960. 18p. OTS price, \$0.50. (NASA TECHNICAL NOTE D-477)</p> <p>The possible detrimental effects of the low-pressure and radiation environments on the utility of pure metals, alloys, ceramics and other inorganic compounds, plastics, and lubricants are outlined. The state of knowledge with regard to the possibility of predicting behavior is discussed for each of the material classes. The specific areas are described in which further research and gathering of engineering data are needed. The role of space experiments in the various areas is indicated.</p>
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